Homologous peri-oceanic west coast climates in the southern hemisphere

J Gentilli

Department of Geography, The University of Western Australia, Nedlands, WA 6009, Australia

Abstract

Comparisons and analyses of similarities and differences between these climates in the three southern continents have revealed further aspects of the uniqueness of the Western Australian peri-oceanic and coastal climate.

In 1934 Meinardus published his rainfall map of the world, which clearly showed that the driest areas above the oceans were slanted SE-NW between 20° and 10° S off South America and Africa; at their origin, they encroached over the continental shores. The climatically corresponding area off Australia was (a) further south, between latitudes 25° and 20°S, (b) not slanted, (c) slightly offshore, clearly away from the coast, and (d) much smaller. In winter, low cloud, steady rain and passing showers about 30°S are frequent on the Western Australian coast and practically absent from the western coasts of Namibia and Chile (McDonald 1938). The annual rainfall off the west coast at 32°S is nearly 750 mm in Western Australia, under 300 off Chile and under 200 off Namibia. Near 24°S it decreases to under 200 mm off Western Australia, nearly nil off Chile and perhaps 25 mm off Namibia (Gentilli 1952a).

Biel (1929) had already shown that rainfall also varied to a different extent and over very different areas in the three southern continents, the Australian region of high variability being the smallest and more clearly restricted in latitude, whereas the South American area of high variability had great meridional extension and came fairly close to the Equator.

Ship observations collated by McDonald (1938) recorded about the same prevalence of southerly winds along the western subtropical coasts of the three continents, but their force was greatest near Western Australia and lowest near Chile, where calms were most frequent. Haze was more frequent near the African coast.

World maps of surface air temperatures for January and July (*eg* in Blüthgen 1966 or Newton 1972) and for each month (NOAA 1984 ff.) show equatorward bending of isotherms along the western coasts of all continents except Australia.

Atlases and books contain small rainfall maps, but in general the class intervals between isohyets do not allow adequate intercontinental comparisons. It was well known that dry climates continued equatorwards in South America and Africa, but since the Western Australian coast slants north-eastwards and eventually eastwards (Cape Londonderry, its northernmost point, is at 14°S) the pursuit of these and similar comparisons just did not eventuate.

Progress in meteorological observations and recordings has made it possible to analyse more climatic data in more sophisticated ways, thus isolating additional significant climatic information. Dynamic climatology, particularly with regard to the frequency, morphology and behaviour of tropical cyclones and the subtropical jet stream, has added to the knowledge and understanding of climatic differences between these homologous coastlines. The relevant factors and events may also originate at great distance, as is the case with El Niño, but are nevertheless very significant - their significance being subject to a considerable time lag.

A detailed comparison of the climates of the southern continents' western coasts shows differences which can be traced back to latitudinal extent and vertical configuration. Upper air analysis shows promise and some evidence of meaningful relationships as well as significant regional differences.

Most important regional climatic differences however are due to ocean water circulation and particularly differential surface temperatures.

Introduction

The term *homologous* defines the latitudinal limits of this study: west coasts occur in all three continents in the Southern Hemisphere, but the Western Australian coast has the shortest span of latitude (only between 14 and 35°S) and is therefore the maximum common factor. Africa and South America continue further north towards the equator, and South America continues further south into the higher latitudes. The term *peri-oceanic* has been added in order to include the climate of the air above the coastal waters, distinct from the climate of coastal and interior localities and more closely associated with ocean surface temperatures. Such concepts are illustrated by Fig. 1, which appears after the historical section. The position of the three regions on the globe places each one of them under the influence of the eastern margin of the quasi-stationary anticyclone which dominates the ocean offshore (Alissov 1954), but the degree of this influence is already a valid differential criterion, with western South America rigidly controlled by the Andean barrier, southwestern Africa occasionally swept by continental influences, and Western Australia being more continental than oceanic alternately in the north and in the south at the opposite seasons of the year. Such differences are shown, for instance, in Fig. 6.

Early observations: Western Australia

Early, isolated observations of these climates did not allow any comparative analysis, but on the other hand were not hidebound by official rules and allowed more scope for keen individual observers. Captain King (1827) made careful weather observations along the Western Australian coast between 1818 and 1822. In 1827 Captain Stirling observed "that the sea-breeze on this coast is usually at S.S.W., and is therefore charged with moisture and very cool; this moderates the action of the sun in summer... It is also remarkable that the [early morning]* land wind blowing from these mountains [presumed higher and snow-capped further inland!] is a cold wind... and from the alternate operation of these two winds, which seldom leave an intervening calm, the air, notwithstanding the sun's great heat, is cool and agreeable, except in spots which are sheltered from the breeze, or during calms" (in Cooke 1905). Some of the earliest climatic observations at Perth, published by Irwin in 1835, were quoted by Mühry (1862): "there are two seasons, the *wet* and the *dry*; the former, winter-like, lasts from March until November, with heavy rains only in August and September [should be June and July!]; the height of the rainless summer time is in January... Abundant dew is seen every night." Mühry adds that "the rains must come with northwesterly winds... Summer dew [at times!] condenses notwithstanding the continental easterlies because of the proximity of the sea as a source of moisture and the nocturnal cooling under a clear sky." Of 838 mm annual rainfall at Fremantle, 482 come in the three winter months (279 in July alone) and only 38 in the three summer months.

Cooke (1901, 1905) pointed out that the winter "sets in, as a rule, rather abruptly" and gave the dates of the first heavy winter rains at Perth from 1880 to 1905. "Owing to this tendency for the rain to fall principally in heavy showers and at night... the general impression of the Perth winter is that of a succession of fine, bright, calm days, varied occasionally by a severe but brief storm. The weather is, on the whole, delightful, but it may perhaps be too mild... The summer does not quite set in quite so abruptly as the winter. With an occasional hot day in October, it commences generally in November... On a normal hot summer day a sea breeze always sets in about noon on the coast, and reaches Perth about 2 p.m. The temperature then commences to fall, and the evening and night are delightfully cool and pleasant... The appearance of soft, watery cumulus clouds in the West, generally about sunset, announces the arrival of the welcome change... At night probably a few light showers, and we realise that a definite change has occurred."

Johnston (1848) remarked that "...the south-east trade or passage wind extends... from about latitude 10 to 20 degrees south, within which limits it blows powerfully, and with great steadiness, from April to October... During the hot season... the space between the [equator's] line and 10 or 20 degrees south, is occupied by the north-west monsoon, which then attains its southernmost limit... South of the zone of the trade winds, we find the district of the north-west winds..." Cooke (1901) confirmed that north of the tropic "the year may be divided into two seasons - wet and dry; the former lasting from the middle or the end of November to the end of March. During this period the weather is very unpleasant, the maximum temperature every day being close to or above 100°F (37.8°C), and records of 110°F (43.3°C) are by no means infrequent. [In a previous edition, Cooke had mentioned press telegrams, perhaps from Onslow, stating that "a delightful cool change has set in; the shade temperature has dropped to below 100 deg." (37.8°C) but this mention was omitted in 1905]. Thunderstorms, accompanied by heavy rain, are frequently experienced, and it is during this season that the willy-willy [tropical cyclone] occasionally visits the North-West coast. A moderate rainfall can generally be relied upon down to about latitude 20 degrees... In the winter months, or dry season, the climate is considered by the inhabitants to be most enjoyable..."

Early observations: South-West Africa

Monteiro wrote in 1875 that at Mossamedes (Moçàmedes, Angola, 15°15'S) "near the coast there blows a strong sea breeze from 9 or 10 hours until about sunset, often too strong to be comfortable... In the hot season temperatures rise to 22 or 24°C, rarely to 32°C. In the cool season it rises to 22 to 24°C, to fall nightly to

* Square brackets [] indicate words or sentences inserted to clarify the original text

15 to 18°C. The nights are so cool that for about six months one finds a blanket comfortable at night" (Hann 1910). At Tiger Bay (Bahía do Tigre, 16°45'S) Chun (1903) had found that Negro women preparing the fish ashore "wore sheepskin jackets for protection from the cool wind." At that time freshwater, totally lacking in the area, had to be brought in from Mossamedes.

Mühry (1862) quoted from the official 1842-56 observations, much more informative, particularly with regard to the moderate rainfall, the summer drought [which, as in Western Australia, extends throughout March as well] and the scarcity of thunderstorms. Dew is plentiful near the coast. The climate of Namibia (formerly German Southwest Africa) "is dominated throughout the year by cool southwesterlies, even stronger in summer. Ocean water at Walvis Bay has a surface temperature of 12 to 15°C and southwards to Angra Pequena 10 to 12°C, which explains the temperature of this coast, uniquely low for its latitude. The coastal land strip dominated by these cool winds is about 70 to 100 km wide. It is practically rainless, quite a desert, covered by sand dunes, which the frequent fogs moisten only superficially. The daily and annual range of temperature is narrow, the cloudiness brought by the frequent sea fogs is great. In contrast with this stands the climate of the interior... It is very difficult to shield the thermometer from radiation by the heated ground, walls in the sunshine, etc." (From a report in the *Petermanns Geographischen Mitteilungen* of 1894, quoted in Hann 1910). "The densest fogs, which can wet right through in a short time, are limited to a coastal strip some 30 km wide; further inland to a distance of up to 100 km from the sea they are less frequent and lighter; in the higher interior they are absent or very rare..." (Pechuël-Loesche 1886, quoted by Hann 1910). "Thunderstorms travel [from the interior] from East to West. While they move towards the sea, they never cross the coast, above which they dissolve. Walvis Bay had one thunderstorm in years... Swakopmund and Windhoek lie on the same latitude, and Windhoek at 1660 m of altitude is 4°C warmer than Swakopmund on the coast, in December and January some 6.7°C" (Hann 1910).

During a morning walk at Walvis Bay one noticed "still air, and a thick grey blanket of cold fog enveloping the beach. It dripped from the roofs like a gentle rain and the upper layer of soil is wet through, but a few centimetres below the surface it is dust dry... The humidity of the air reinforces the cold sensation... The fog dissipates before 10 or 11 hours and the sun breaks through. The horizon remains dusty and the extraordinary humidity by noon gives a muggy oppressive sensation, even while the thermometer rarely shows more than 25°C.... After sunset the fog rises again from the sea..." (Dove 1897, quoted in Hann 1910).

The hot dry winds (the *berg* winds) that descend from the interior to the coast "are not desert winds, but Föhn winds, which owe their high temperature to the descent of the air from the high interior..." (Hann 1911). They blow from late April to June and are "the most remarkable phenomenon of this whole coast as far as Port Nolloth... They warm the air up by 7 to 9°C and lower the relative humidity quite remarkably" (Hann 1911).

Early South African observations were quite fragmentary: Kaemtz (1843) for instance wrote that at the Cape of Good Hope [Cape Town Observatory] mean temperatures were: winter 14.8, spring 18.6, summer 23.4 and autumn 19.4°C. These values were based on 7 to 11 years of observations. "The average relative humidity reaches 74% for the year, the driest month (February) has 64%" (Lorenz & Rothe 1874). Hann (1911) wrote a good climatological description: "In Cape Town southeasterly winds dominate in summer, northwesterly winds in winter. In the summer half-year (October to March) the southeasterly reaches significant force and often blows for a week or two without interruption, stirring up masses of dust and making things very uncomfortable. On the other hand it is also a blessing, renovating the stagnant air in the hollow below the Table Mountain; it earns the name of 'Cape Doctor'... The force of the wind is so considerable and in summer it blows so persistently that in unprotected spots all tree trunks lean towards the North... Northwesterly winds dominate in winter; they bring moist air, thick clouds and the rainy season..." The greatest contrast in rainfall in southern Africa is between the exposed upper slopes of Table Mountain and Port Nolloth, also on the west coast.

Early observations: Western South America

Johnston (1848) published the observations made by A. von Humboldt in 1802: "The perceptible amount of cold which is felt in the tropics, a few feet above the surface of the ocean in the so-called Desert of Lower Peru, is owing to the low temperature of the sea, and the interrupted action of the sun's rays during the period of the garúa." Mühry (1862) quoted also from Humboldt: "the Antarctic Current [later renamed the Humboldt Current] brings a considerably lower temperature along the western coast of South America..." Lima's temperatures "are lowered by about 3° Réaumur [3.75°C] by the [thermal] anomaly of the Antarctic Current..." Duperrey in March 1823 found the air at Callao (Lima) to be at 20.2°C, about the same temperature as the ocean surface, and some 6°C cooler than the average air temperature at the same latitude (Johnston 1848); Johnston showed the 70°F (21.1°C) air isotherm west of Chile bent equatorwards by about 7 degrees of latitude and that of 60 °F (15.5°C) by about 9 degrees.

"As a result of the condensation of fog in the winter two annual seasons are distinguished, the aptly named colder overcast, from May to September, and the warmer clear sky, from October to May. In November one begins to see the stars, which remain visible until April; then appear the stationary fogs, *garúas*, and the solar disk remains yellow-red for weeks on end ; even in summer it could so appear occasionally. This applies to the whole Peruvian coast, which receives no rain." From a note written by Humboldt in 1845 (also based on his 1802 observations and quoted in Johnston 1848): "The vapours of the *garúa* of Lima are so thick that the sun seen through them with the naked eye assumes the appearance of the moon's disc. They commence in the morning and extend over the plains in the form of refreshing fogs, which disappear soon after mid-day, and are followed by heavy dews which are precipitated during the night." Ships "at the time of the garúa... are unable for several days to obtain any observations for latitude; and, prevented by the fog from ascertaining their position on the coast, they are often... carried past the harbour... The mist and fog are most dense between Pisco [13°52'S] and Lima." Darwin (1839) wrote that in July 1835 "during our whole visit the climate was far from being so delightful as it is generally represented. A dull heavy bank of clouds constantly hung over the land, so that during the first sixteen days I had only one view of the Cordillera behind Lima... It had almost become a proverb, that rain never falls in the lower part of Peru. Yet this can hardly be considered correct; for during almost every day of our visit there was a thick drizzling mist, which was sufficient to make the streets muddy and one's clothes damp: this the people are pleased to call Peruvian dew." Lima is in the rain-shadow of the trade winds (Fig. 2) "which extends a further 40 miles over the ocean, and in consequence there are no storms on this coast." G. Birnie, ship surgeon, wrote in 1824 that the main characteristic of the coastal strip of western South America from 5 to 30°S (Payta to Coquimbo), about 370 miles long and only 14 wide, is "that no rain falls and the sun is mostly covered by a curtain of clouds (the latter as a consequence of the lower temperature of the Antarctic Current). Thereby this coast is a barren desert... The mean temperature may be estimated at 18° Réaumur [22.5°C]."

As to much of Chile in general, Mühry quotes Molina, whose work was published in 1782, saying that "northern Chile suffers its drought because of the persistent trade winds, with some indication of the transition from the tropical to the subtropical belt by cloud formations in summer and in winter; in the middle tract the subtropical belt takes over with winter rains and rainless summers... This long-stretching land is one of the finest in America, because of the clearness of its sky, the constant mildness of its climate... From the beginning of spring till the autumn the sky over the land between 24° and 36°S is constantly clear; there is seldom a year in which in this period even a light rain falls... In central Chile the rains begin in mid-autumn, *ie* in April, and continue through the winter till the beginning of spring, *ie* the end of August. The rains increase from North to South. In the northern provinces, Copiapò (27°S) and Coquimbo (30°S), they are scarce; in the central provinces however it rains three or four days without interruption, followed by 15 or 20 clear days... Thunderstorms are very rare."

When there is a break in the stratus cloud or fog, the intensity of insolation reverts to normal: "proceeding inland, warmth increases up to an altitude of over 300 m, particularly in summer" (Lorenz & Rothe 1874).

Of Iquique (20°12'S) Darwin (1839) wrote that "the whole is utterly desert. A light shower of rain falls only once in very many years... During this season of the year [winter], a heavy bank of clouds extending parallel to the ocean, seldom rises above the wall of rocks on the coast... Water is brought in boats from Pisagua, about forty miles to the northward... On the coast mountains, at the elevation of about 2000 feet [about 600 m], where during this season the clouds generally hang, a very few cacti were growing in the cleft of rock... Whatever its origin may be, the existence of a crust of a soluble substance over the whole face of the country, shows how extraordinarily dry the climate must have been for a period long antecedent."

In 1887 Ball (Hann 1910) wrote that at Tocopilla (22°10'S) "the view was absolutely that of a moonscape, a world without water", but at Antofagasta he was told that heavy rains fell once in 5 or 6 years [rains associated with El Niño?].

Copiapò (27°22'S) at 395 m "is every morning enveloped in thick fog which reaches as high as Pabellón, about 275 m higher, where the sky is always clear. One can only see some clouds very far to the West. Rain falls at Copiapó once or twice a year, often consisting of a few drops" (quoted in Hann 1910). Darwin (1839) had written that (at Copiapó) "after two or three very dry years, perhaps with no more than one shower during the whole time, a rainy year generally follows; and this does more harm than even the drought... Once for a period of thirty years not a drop [of running water] entered the Pacific. The inhabitants watch a storm over the Cordillera with great interest; as one good fall of snow provides them with water for the ensuing year. This is of infinitely more consequence than rain in the lower country. The latter, as often as it occurs, which is about once in every two or three years, is a great advantage... But without snow in the Andes, desolation extends throughout the valley." In the Andes "the winds of these lofty regions obey very regular laws: every day a fresh breeze blows up the valley, and at night, an hour or two after sunset, the air from the cold regions above descends, as through a funnel."

At Valparaíso in late July Darwin (1839) noticed that "after Tierra del Fuego, the climate felt quite delicious - the atmosphere so dry, and the heavens so clear and blue with the sun shining brightly, that all nature seemed sparkling with life... Here, during the summer, which forms the longer portion of the year, the winds blow steadily from the southward, and during the three winter months [rain] is however sufficiently abundant... I did not yet cease from wonder, at finding each day as fine as the foregoing."

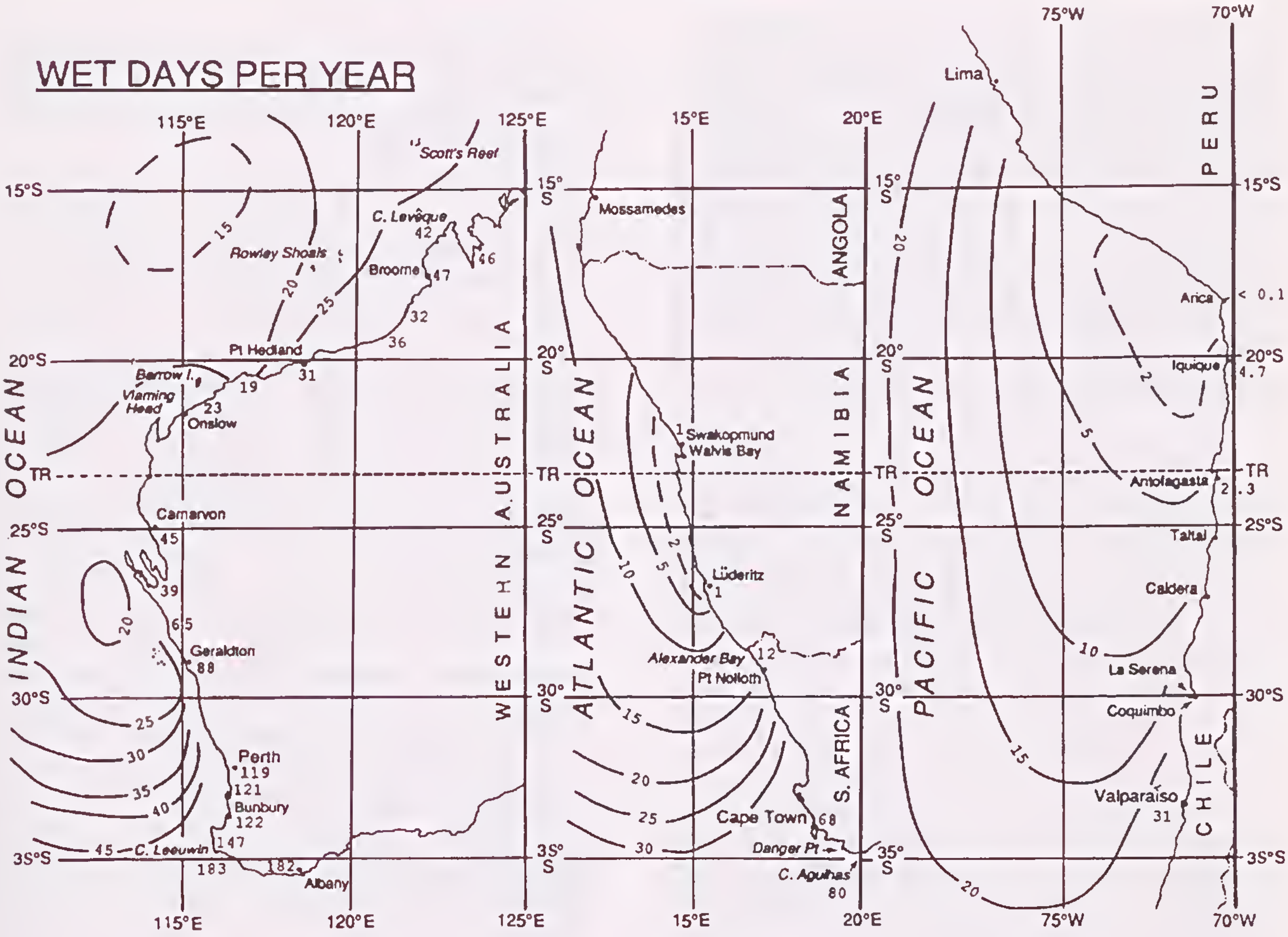

Figure 1 Outline of the regions studied and number of wet days per year offshore (from ships' observations) and at coastal stations.

Although these regions were treated in separate chapters, Hann (1910, 1911) used every opportunity to make penetrating inter-regional comparisons. The only modern avowedly comparative study of these climates is due to Lydolph (1957); good but separate evaluations are found in Trewartha (1961). Modern work with many maps on each region's climate is readily available in Schultze (1972) and Höflich (1984) for Africa, Miller and in part Johnson (1976) and Streten & Zillman (1984) for South America, and Gentilli (1971) and Ramage (1984) for Australia, besides many localised or specialised papers, most of which are referred to in the text and listed as references.

A hierarchy of climatic factors

1. *Planetary location.* The basic factor in this group is *latitude*, with the consequential seasonal changes in *insolation* and the many derived changes in temperature, air circulation, moisture mobilisation and transport, affected and modified by many factors further removed from the initial planetary pattern. By and large, these latitudes are principally influenced by subtropical anticyclones, which consist of descending and therefore dry air, eventually spreading equatorwards along the surface as the well known trade winds. In Hettner's (1930) genetic classification of climates these regions mainly have a dry trade-wind climate extending northwards to *ca* 8°S (over 2600 km) in Chile and Peru, 18°S (1200 km) in Namibia, and only 22°S (560 km from N to S) in Western Australia. At the southern margin (25 to 30°S) the anticyclones alternate seasonally with mid-latitude depressions; the anticyclonic winds dominate the hot season, which they contribute to make drier. From these winds' ancient name, Hettner called this alternating type of climate Etesian. The seasonal persistence and the alternations of wind regimes are clearly shown in a map by Köppen (1931), which gives a first basis for the differentiation of the three regions: western South America with the least modified trade-wind regime, southwest Africa where the trade winds are slightly deflected towards the coast, and Western Australia with wind alternations and modifications, and isobaric troughs (Gentilli 1969).

2. *Continental geometry.* The most significant differences between the three coastlines were outlined at the beginning of this paper (Fig. 1). Most important are the slanted very broad opening towards the equator north of Australia (which favours water exchange, Southern Oscillation impulse transmission and the development of monsoonal and pseudo-monsoonal air

circulations) and the extension of South America into the higher latitudes, leaving perhaps southern Africa, in this respect, as the intermediate 'norm'. Continental influences exaggerate both hot and cold thermal extremes and oceanic influences reduce them. Concave shorelines allow continental influences to affect the air further seaward (*eg* Eighty Mile Beach, Shark Bay, Walvis Bay and Alexander Bay), thus increasing temperature ranges; convex shorelines have the opposite effect, recorded on the many capes and few small islands on the continental shelf. At these latitudes western meridionally - aligned coastlines give rise to strong land- and sea-breezes, as mentioned in 5 below.

3. *Oceanodromy* (ocean flows). The great southward extension of South America intercepts the West Wind Drift, deflecting most of it towards the equator as a relatively cool current. The remainder is deflected polewards and only past 52°S resumes its course as a colder segment of the Drift heading towards South Africa. Off Namibia the southerly wind that drives the current probably causes and certainly entrains some colder water upwelling along the coast (see 5 below). Lettau, in an appendix to Johnson (1976), ascribes the ascent of deeper and colder water off Peru to the Ekman effect within the Humboldt Current; Streten & Zillman (1984) write that "the coldest water, off the shore of Peru, stems mainly from wind-induced upwelling". These ocean currents and upwellings effectively cool the coastal strips of both continents, making a shallow layer of overlying air cooler and most stable, and consequently almost rainless notwithstanding very high relative humidities (Fig.5).

Breuer (1974) shows the average annual boundary between prevalently stratiform and cumuliform clouds (respectively in stable southern and unstable northern air) on the west coast of South America from about 42 to 11°S. In the summer it moves slightly offshore and becomes much narrower from the tropic to 16°S, where it ends.

In Western Australia a NNW-SSE orientation of the coast prevails from 23°S, whereas it occurs from 18°S in south-western Africa, and only northwards from 18°S in South America (Fig. 1). The gap to the north of Australia, so vital for the dynamics of the oceanic circulation, indirectly has a very significant effect on climate, allowing warm Pacific water to enter the Arafura Sea during the Australian autumn and winter. "There lack on the west coast of Australia the cool ocean currents (and the upwelling cold water) which so effectively lower temperatures on the west coasts of southern Africa and South America..." (Hann 1911). Dutch ship observations of rare mists and fogs far off the West Kimberley coast and west of 108°E a long way off the Pilbara coast (Koninklijk Nederlands Meteorologisch Instituut, 1949) suggest occasionally contrasting water and air temperatures. The Cocos-Arafura ocean region has mostly clear skies and receives over 185 Wm^{-2} per year on 1,160,000 km^2 160 to 185 Wm^{-2} on another 2,175,000 km^2 and 135 to 160 Wm^{-2} on another 3,800,000 km^2. Off Peru and Chile, because of stratus and fog cover, the best annual average radiation intake is 135 to 160 Wm^{-2} over some 300,000 km^2 with the remainder below 135 (calculated from Gorshkov *et al.* 1974).

The general trend of the coast and the position of the anticyclones over the oceans to the west affect the impact or otherwise of the anticyclonic margins on coastal waters and coastal air as well (see 4 below).

4. *Orography*. The remarkable difference of forms between the three continents is shown in Fig. 2. The cross-section is taken along the tropic; on the western margin of South America the Andes are a very effective climatic barrier, crossed very seldom by weather disturbances from the Pacific, which lose much of their energy during the uplift (South African Weather Bureau, 1957-58). An important consequence of this barrier effect is that the surface winds from the South Pacific high-pressure system run northwards along the coast of South America, whereas the homologous winds from the South Atlantic system can spread for some distance inland, assuming a south-south-westerly direction over the Namibian coast. The rain-shadow effect of the Andes on any possible easterly air flow is enormous, and the desiccating effect on any air descending their slopes is noticeable, although other factors (para. 3 and 5) combine to cause the total dryness of much of the Atacama Desert. Every valley is swept by a westerly valley breeze in the morning and an easterly mountain breeze in the afternoon, which may continue as a land breeze at night; from the observations of Miller (1976) one would surmise the arising of true land- and sea-breezes diagonally across the shore and the western foothills of the Andes.

Both Australia and southern Africa have a raised rim on their eastern margin. The height of the African Plateau is sufficient to allow surface atmospheric interchange while increasing the contrasts between easterly and westerly weather systems, modifying both, strengthening any katabatic (Föhn) effect on descending easterlies and contributing to make the Namibian coast one of the most extremely arid regions in the world. One of its peculiarities is that in the cooler season, and particularly in May-June, these exceptionally dry and hot berg winds from the interior, heated adiabatically, make temperatures rise above 40°C and humidity sink to below 10% (Köppen 1931).

The low Western Australian Plateau allows free transit to weather systems, introducing only distance travelled overland and the interior's overheating as modifying factors and, where topography aids, a mild katabatic (Föhn) effect noticeable in hot summer easterlies and in the mean maximum temperatures at *eg* Nyang, Marble Bar, Gascoyne Junction. The significance of clear skies in the radiation budget may be assessed from 3 above.

5. *Hydrothermostasy* (thermal condition of water). Its distribution is directed by the movements of the water

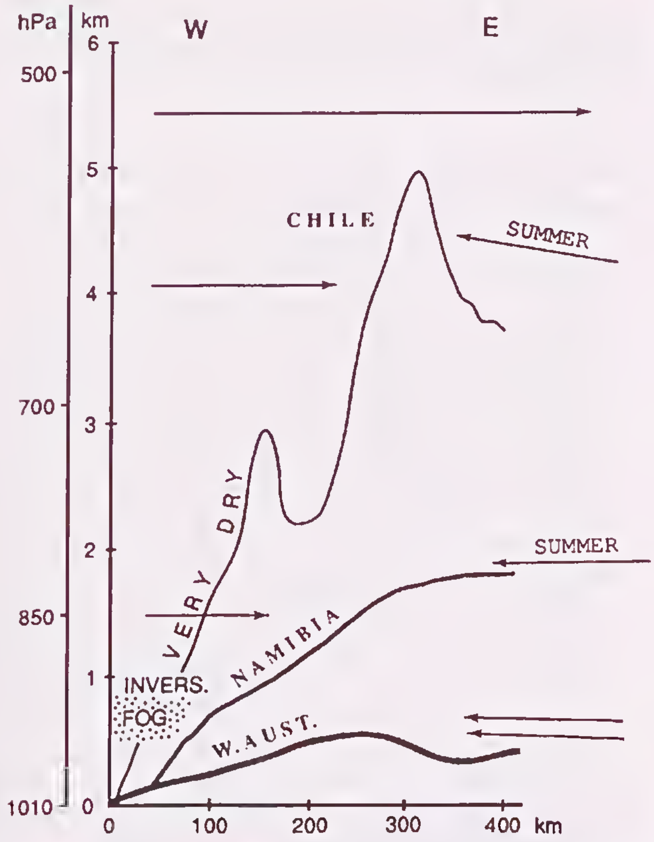

Figure 2 Cross sections of the three regions along the tropic, main seasonal winds, and average position of the inversion and the underlying fog on the Chilean coast.

masses as in 3 above, but the initial amounts of heat, the rates of change and/or dispersal and rises and falls in thickness and in level are also largely affected by solar radiation, evaporation, etc. Along the Namibian, Peruvian and north Chilean coasts the upwelling of cool ocean water is a very powerful climatic factor, cooling and stabilising the overlying air and thus preventing any convection (no thunderstorms), condensing most of the moisture into fog and almost preventing any fall of rain (Figs. 4 and 6). Near Western Australia south equatorial water stored (Gentilli 1972) and further heated in and around the Arafura Sea adds a considerable amount of heat and moisture to the overlying air, causing instability and thunderstorms (95 days with thunder at the former Kunmunya Mission, 15°25'S,125°43'E). The "El Niño" phenomenon which episodically conveys warm water along the Peruvian coast is well explained by Streten & Zillman (1984) who also list its occurrences in previous years, overlapping with Schott's (1932) much longer historical series. The occurrence of convective (cumuliform) clouds has been mapped by Matsumoto (1989) using their interception of longwave radiation; a regional differentiation clearly emerges, particularly with regard to Western Australia.

Atmospheric circulation

Fig. 3, drawn from NOAA 1988 data for Perth and Cape Town and 1984 data for Valparaíso, shows that at 200 hPa (*ca* 12,000 m) stratospheric winds (mostly of jet speed) blow stronger above Perth than above Cape Town or Valparaíso almost throughout the year, with notable gaps only in summer. The greatest difference is noticed from May to October and appears stronger between Perth and Valparaíso. This is confirmed by van Loon *et al.* (1971) who for July show at 200 hPa and 30°S a mean geostrophic zonal wind of over 52.5 ms^{-1} across Australia, 37.5 to 40 ms^{-1} off Namibia and between 32.5 and 35 ms^{-1} off Chile. Along 20°S the wind slows down to about 20 ms^{-1}; consequently, Western Australia experiences a most dramatic contrast between subtropical and intertropical latitudes. Perth has relatively windier springs and summers.

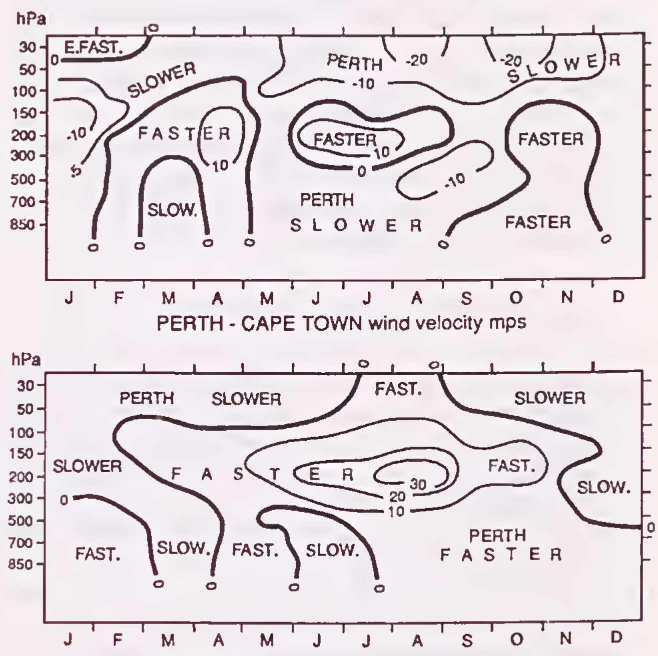

Figure 3 Difference in wind velocity, in metres per second, in the atmosphere up to 30 hPa (about 23 500 m) above Perth and Cape Town and Perth and Valparaíso respectively. Notice the 200 hPa belt where Perth is overflown by much stronger winds than the other two stations.

The descending trend of westerly winds is particularly noticeable from May to July, when isobaric heights above Perth are distinctly lower. At 500 hPa and about 25°S van Loon *et al.* (1971) show westerlies entering Western Australia at over 17.5 ms^{-1}, Chile at about 12 ms^{-1} and Namibia at 10 ms^{-1}.

Much of the additional energy in the atmosphere above the Western Australian coast derives from the additional solar radiation received, from a direct greater latent energy input (from the inflow of sub-equatorial waters) as well as storage (heat stored in ocean waters off northwestern Australia). Southwestern Africa and South America show the effect of energy sinks (loss of atmospheric heat to the cool water masses off their shores).

West of the three land masses lie semi-permanent oceanic anticyclones which, subject to the latitudinal displacement normal with the seasons (see above), send persistent southerly winds along the shores. This effect is strongest in summer and weakest in winter, when it is overcome by the transit of frontal depressions, which occur in all three regions, but much more regularly and frequently over Western Australia.

These southerly winds are strongest along the Benguelan and northern Namibian shores (see historical part above). Writing on the absence of pelicans, Shannon *et al.* (1989) suggest that "it seems probable that the winds of the Benguela coast, apart from at a very few sheltered sites such as Walvis Bay, are simply too strong for these birds' aerial manoeuvres." As is normal within the anticyclonic periphery, they are quite shallow: McGee (1988) gives them a frequency of 41% at Cape Town, but shows them decreasing sharply with height, whereas nor'westerlies, which are 28% of surface winds, become increasingly frequent with altitude to at least 300 hPa (*ca* 9000 m), where they are totally dominant.

Monsoons, tropical cyclones and epitropical disturbances

Because of its configuration, Australia is the only southern land mass which gives rise to a monsoonal circulation, albeit a weak one. Particularly with regard to Western Australia it may be called a pseudo-monsoon (Gentilli 1971) because it is very shallow and seldom involves trans-equatorial air, which is the normal surface component of a full monsoonal circulation (although Ramage (1984) takes a seasonal 90° change in wind direction across a coastline as sufficient proof of a monsoonal circulation); most of the summer westerly flow into the Kimberleys, as clearly shown for instance by Ramage (1984) in his Fig. 16, is air from the high-pressure belt to the west of Australia, initially very dry because of its slow descent as part of an anticyclonic system, steered towards the Kimberleys by the northern margin of the almost stationary Pilbara low. Matsumoto (1989) writes that the Australian monsoon season, lasting about 80 days, "is the shortest among all continental wet periods in the tropics."

Fig. 4 shows the mean monthly rainfall received at each latitude: a large area including all the Kimberleys receives much of its rainfall, from December to March (the "wet"), from this pseudo-monsoonal circulation and thunderstorms. Matsumoto (1989) shows two parallel lines of low outgoing radiation in the Australian region, the main one (caused by truly monsoonal cloud systems) being just to the north of Australia, and the weaker one running from the Kimberleys to north Queensland.

Tropical cyclones need an ocean surface temperature of at least 28°C as a source of energy and a latitude sufficiently far from the equator to allow the Coriolis effect to initiate the rotation of the system. These requirements exclude them from southwestern Africa and South America, while allowing them to occur several times a year in Australia (Coleman 1971 and Lourensz 1977).

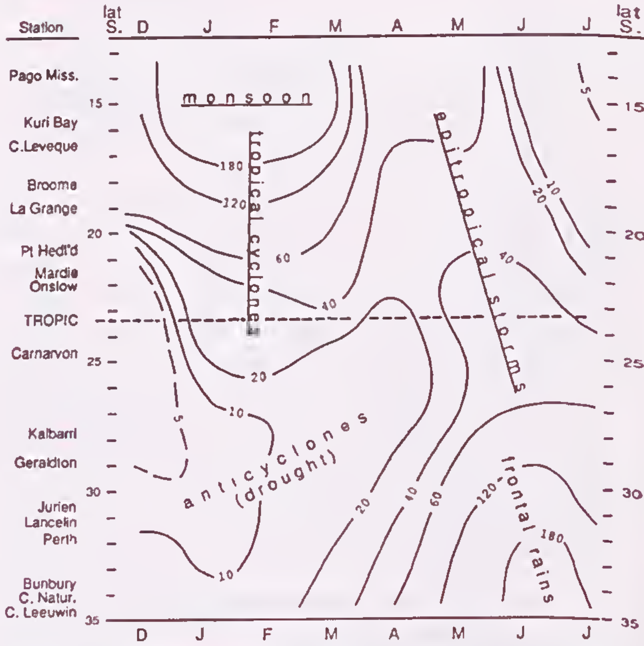

Figure 4 Chronolatitudinal graph showing the average monthly rainfall at coastal localities in Western Australia. The underlined rain-bearing systems (monsoon, tropical cyclones and epitropical storms) do not occur in southwestern Africa or South America.

The immense and concentrated energy of tropical cyclones transports enormous masses of water vapour to the subtropical latitudes, with occasional incursions into the middle latitudes. Fig. 4 shows this southward transport of moisture as mean monthly rainfall in each latitude; as far south as Broome the contributions of monsoons and cyclones may differ little in overall quantity, but cyclones are far less frequent and infinitely less reliable. Their average annual contribution to Western Australian rainfall (mostly restricted to a few days in January) ranges from some 400 mm in the northern Kimberleys to 200 mm at Broome and just under 50 mm at Carnarvon (Milton 1978). In practice, averages are almost meaningless when cyclones are concerned: in an arid region one cyclone may bring half the mean annual rainfall in three or four days.

Epitropical disturbances are peculiar to Western Australia (Gentilli 1973, 1979a). They mostly occur from May onwards, when the water at lower latitudes is not warm enough to start a tropical cyclone. The uplift of moisture is usually provided by massive thunderstorms over Indonesia or the Arafura Sea, or occasionally by a tropical cyclone. Tapp & Barrell (1984) plotted the 'tropical extremities' of 53 'North-West Australian cloud bands' (the present official label for the phenomenon) between September 1978 and August

1982 inclusive and found that 25 appeared between 7°30' and 12°30'S and 87°30' and 112°30'E. They are conveyed below the subtropical jet stream (belt of strongest winds in Fig. 3) and travel southeastwards as 'upper air disturbances'. The amount of rain which they can bring varies, but is sufficient to make May wetter than April or June over most of the Pilbara, and to give many localities a secondary peak of rainfall in that month (Fig. 4). Tapp & Barrell (1984) counted 6 such events in April, 8 in May, 10 in June, 8 in July. The frequency of these epitropical disturbances varies from season to season and year to year, mainly according to the frequency of strong subtropical jet streams. They often only show the well described 'cloud band' of satellite images (Downey *et al.* 1981, Tapp & Barrell 1984, Kuhnel 1990) and may be the cause of slight changes in long-wave radiation emission between Exmouth and Port Hedland in Matsumoto's (1989) April and June records. Their average contribution of rainfall to Onslow or Mardie, about 40 mm a month, may seem to equal that from tropical cyclones, but in reality cyclones may occur once or twice a season while epitropical disturbances may transit every week, particularly in late autumn and early winter.

No such phenomena occur in Africa or South America. However, Harrison (quoted by Tyson 1986) identified the South Atlantic cloud band associated with a cyclonic poleward tract (accelerating) at 200 hPa (about 11,000 m) between about 18 and 35°S. As in Australia, the anticyclonic bend in the subtropical jet stream rises and slows down, and the cloud band disappears, to reappear again, as over Australia, after the next cyclonic poleward bend. It is suggested here that a most significant difference in the sequence over the two continents is due to the presence of the slightly warmer water in the eastern Indian Ocean: the jet stream increases in speed already before its entry into Australia (van Loon *et al.* 1971), whereas it slows down before entering South Africa. As a result, the wavelength of the meanders is shortened and their amplitude is increased over Australia. Over southern Africa the longer meanders make the cloud band reappear over the warmer Indian Ocean, and the shorter ones pass over Namibia without any visible cloud band (Harrison, in Tyson 1986).

Cloudiness, humidity and rainfall

These regions are unusual because some of their cloudiness is not associated with precipitation. A regional difference is already clear in a map by Hann (1896) with cloudiness varying strongly with latitude off Peru and Chile, moderately so off Namibia, and varying more with longitude off Western Australia. Samoilenko (1966) shows the waters off southern Peru and northern Chile with a July cloudiness of 6.4 to over 7.2 oktas where the rainfall for the month is under 5 cm with a probability of less than 5%. This is due to the steady inversion overhead which prevents the moisture below from rising, maintaining a relative humidity around 80% for the year (Száva-Kováts' map, in Blüthgen 1966). Off Namibia and South Africa the average relative humidity is over 70% with a July peak of 80% at Port Nolloth, which has minimal cloudiness and a total annual rainfall of 64 mm. Humidity decreases very rapidly towards the interior.

Off Western Australia, from Port Hedland to Derby (excluding Broome), July cloudiness is below 1.6 oktas (measured by nephanalysis, Ramage 1984) and relative humidity is below 50%. North of 30°S it still is less than 70%; fogs are rare, cloudiness and rainfall vary in nearly direct proportion. In respect of atmospheric moisture, Western Australia may truly be considered the most 'normal' of the three regions.

This 'normality', in a predominantly continental environment, leads to greater daily ranges of temperature, which in turn cause relative humidity to vary very widely. While the 3 pm observations are fairly close to the daily RH minimum, the 9 am observations are already - and specially in summer and with hot weather - below the daily RH maximum. The Council for Scientific and Industrial Research (1933) and the Bureau of Meteorology (1956) published mean relative humidity values, but these were omitted from later publications in which, at best, 9 am and 3 pm values are shown.

The three regions differ considerably in the amount of precipitation they receive (Fig. 5). In Western Australia the incursions of moist tropical air from whatever source bring large amounts of water vapour which may be condensed and released in very heavy showers (Walpole 1958). A mean rainfall intensity of 15 mm per wet day occurs where more tropical cyclones cross the coast between Port Hedland and Onslow [but there are very few wet days!]. North of the tropic the mean rainfall per wet day varies between 10 and 15 mm, decreasing further south to less than 5 mm on the south coast. South of the tropic, mid-latitude depressions bring most of the rain, apart from tropical incursions of cyclones and disturbances mentioned above.

In southern Africa heavy falls are brought by eastern weather systems, but much of the moisture is reabsorbed in the descent from the plateau. Occasionally depressions "which developed over positive sea-surface temperature anomalies in the south-east Atlantic Ocean" (Walker & Lindesay 1989) bring heavy rains; rainfall is increased at first by the gradual rise over the plateau as the fronts progress inland (Weischet 1969).

In South America the Andes interpose an impassable barrier to any rain-bearing system from the eastern side of the continent; the rare falls from southwesterly fronts are usually very light. An outstanding peculiarity of the South American west coast is the occasional occurrence of El Niño, a warm, southward current which flows temporarily between the cool Humboldt Current and the coast, rendering the overlying air humid and unstable and causing very heavy falls of rain, amounting to more than the annual average within a few wet days (Conrad 1936).

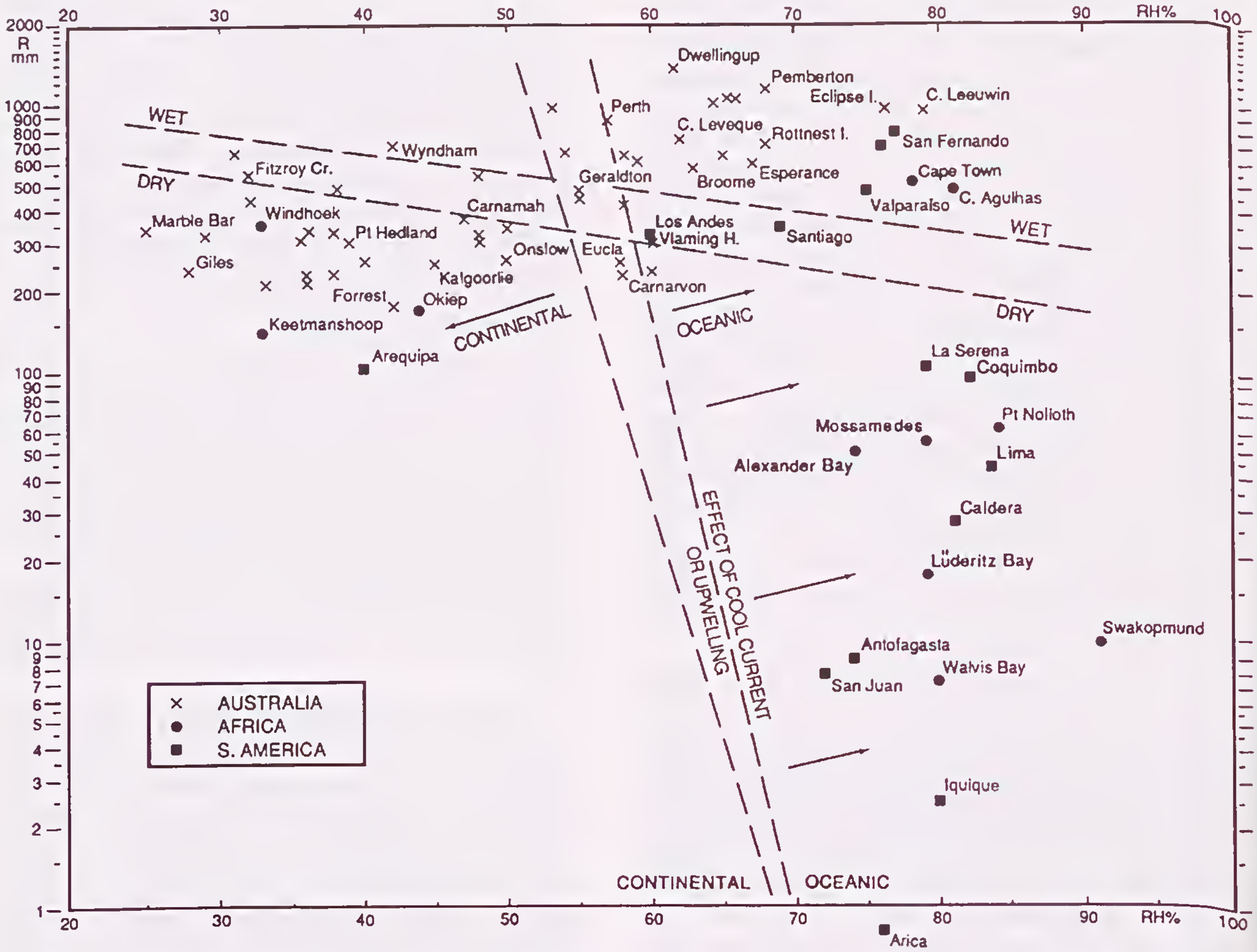

Figure 5 Regional differentiation by combined annual rainfall totals and annual average relative humidity. The graph (with a logarithmic scale for rainfall) shows the opposing continental and oceanic influences and the extraordinarily high relative humidities brought about by cool coastal waters.

The disastrous consequences of El Niño at sea are very well known, but floods and landslides in a normally very arid land also cause damages and losses. The effect of the warm Leeuwin Current on coastal rainfall is minimal because of the very limited surface of warm water involved; the relatively good rains on the Australian west coast are rather due to the absence of cool waters as affect the other two regions.

It is not possible to measure rainfall at sea from a moving ship, but it is possible to observe it. Most maps of estimated precipitation at sea are highly generalised; however, the maps in Schott (1935, 1942), Blüthgen (1966) and Korzun *et al.* (1974) show a clear regional differentiation. A narrow area under 100 mm a year includes the Peruvian and Chilean shores from about 8 to 30°S. Schott (1935) shows a narrow coastal strip under 10 mm (the Atacama Desert) running from about 17 to 25°S; Drozdov, in Korzun *et al.* (1974) shows it more restrictively from 20°S to the tropic. In Angola and Namibia the 100 mm isohyet encroaches over the land from about 18 to 30°S (Namib Desert). These maps differ considerably in the Australian region. Schott (1935) shows the annual rainfall gradually increasing westwards from less than 250 mm at Sharks Bay to over 2000 mm in Madagascar; Blüthgen (1966) shows an area with less than 100 mm per year, only about 6 or 7 degrees wide in latitude, situated off Western Australia and not affecting the coast, and less rain in the interior; Drozdov estimates the rainfall of the same area off Australia, like Schott (1935) linking it closely with rainfall over the land, but ranging westwards from under 400 to over 800 mm per year mid-ocean.

The data published by McDonald (1938) showing observations of 'rain in whatever form' at sea have been reworked here and converted to show the mean number of days per year in which rain has been observed (Fig. 1). Official data on the number of days per year with rainfall >1 mm have been shown for the coastal stations, although exact comparisons are not always possible because of the different definitions of wet day (with precipitation = ≥1 mm metric, ≥ 0.01 inch earlier British and U.S.A., with no possibility of conversion, affecting Australian and South African data). Simultaneous observations at sea at Greenwich noon lead to some underestimate in the African region. However, the contrast between the three continents is most remarkable: Arica (Chile) has an average of 0.1 wet days per year, Swakopmund and Lüderitz (Namibia) 1 day, Mardie and Onslow (Western Australia) 19 and 23 days - mostly supporting Korzun's interpretation of the rainfall pattern. Over the area of coastal waters shown, the number of wet days per year rises only to about 20 off Chile, 30 off South Africa, and 45 off Western Australia. Furthermore, the number of wet days on the coast near 35°S is about 1.5 times its offshore counterpart in Chile, twice its counterpart off South Africa and about 3 times its counterpart in Western Australia.

An important regional difference is due to the 'sweep' of rain-bearing systems. Each kind of system - monsoon, tropical cyclone, epitropical disturbance, extratropical front - has a characteristic way of advancing, while at the same time being partly steered by adjoining pressure patterns. In Western Australia they arrive unaffected by colder ocean surfaces to the west or, if coming from the north-west, strengthened by warm water surfaces, and proceed inland almost unimpeded by orographic factors. In Peru and Chile the Andes intensify any fronts from the Pacific at first impact, but eventually fracture and often destroy them; on the Andean foothills Darwin (1839) observed the extreme localisation of a violent rain storm. Shannon *et al.* (1989) write that "rainfall in 'average' years in the Namib normally occurs as 40-50-km-wide storm cells, and not over broader fronts. Consequently, rainfall events are extremely patchy in their dispersion both in space and time."

A good comparison of seasonal rainfall patterns in these regions may be made from Fig. 6, which at first sight appears somewhat forbidding. The average monthly rainfall is shown for three stations in each continent: Perth, Cape Town and Valparaíso in the outer subtropical belt, Vlaming Head, Swakopmund (Namibia) and Antofagasta (Chile) near the tropic, and Cape Leveque, Mossamedes (Angola) and San Juan (Peru) in the intertropical belt. The rainfall is shown on a logarithmic scale to do justice to the highest and lowest amounts as well, and to show rates of variations in their true proportions.

In the outer subtropical belt the three cities receive similarly plentiful amounts of rain from May to October, but Valparaíso has a much drier summer. In the epitropical situation, the rainfall of Vlaming Head shows two peaks, due to tropical cyclones in January-March and to epitropical storms in May-June, as well as to fronts of well developed mid-latitude depressions in June and July. By September the anticyclones dominate the weather and rains are negligible. At Swakopmund the only average rains worth mentioning range from 1 mm in November and January to 2 mm in February, March and April. Antofagasta fares even worse, with 2 mm in June and less than 3 mm in July.

The most succinct statement of these peculiarities is probably still Hann's (1896): "Remarkable is the scarcity of rain on the western coasts of continents in the subtropical, in part even in the tropical latitudes,... from central Chile and as far as Ecuador, the western coast of southern Africa from the River Orange to as far as Benguela... The dryness of these regions depends on the atmospheric pressure... which brings dominant cool winds from the higher latitudes, and similarly also cool ocean currents, flowing in the same direction, which cool the coast... The stronger and more constant these air and ocean currents..., the more extreme the scarcity of rains..." The role of cool upwelling water was not yet known.

In the main, the statistical variability of rainfall is a function of its scarcity, or rather, of the likelihood of rain-bearing systems penetrating a given region; the drier the region, the less often is this likely to happen, hence a higher variability. Biel's 1929 map is highly generalised; it clearly shows the coastal areas of highest (>30%) variability as extending from about 10 to 35°S in Peru and Chile (La Serena 59%) and from about 12 to 28°S in Angola and Namibia (Walvis Bay 33%). A biologist (Seely 1989) writes that "rain is unpredictable" in the Namib desert. On the Western Australian coast the belt with such high variability runs only from 20°S to the tropic, much of it due to tropical cyclones which cross the coast, Mardie being situated on "cyclone alley". Just outside this limited belt, Onslow has a 26% variability, contrasting with reliable Geraldton's 14% and very reliable Perth's 8%.

Other forms of precipitation and turbidity

Important differences between the three regions emerge from an examination of the different types of precipitation and related or in some way similar phenomena. A problem is the counting of days with drizzle, specifically recorded only in northern and central Chile. There are also vocabulary problems affecting the description of fog-related phenomena in some languages (*eg* Meteorological Office 1939 and Zimmerschied *et al.* 1962). Some climatologists (Köppen 1931, Conrad 1936) also refer to possible observer's subjective influences on visibility records during fog, mist and haze.

Drizzle (*llovizna* in Spanish, the drizzling fog popularly known as 'Scotch mist' [but see below under fog]) consists of droplets between 0.2 and 0.5 mm in diameter, *ie* too small to be counted as rain. The table shows that in northern Chile, where its occurrence is recorded even though it cannot be measured, drizzle (loosely called garúa in the Andean region) is by far the most frequent form of precipitation; it is least common at Antofagasta (23°39'S) with only 0.6 days per year. From there it increases slightly northwards, and much more markedly southwards, until south of Coquimbo it gives way to definite and measurable rains.

Fog and mist are often confused and the distinction is rather conventional. *Mist* (with visibility over 1 km) is called *neblina*, also *bruma*, especially at sea, and at times *niebla* or *calina* in Spanish, *Nebel* or *feuchter*

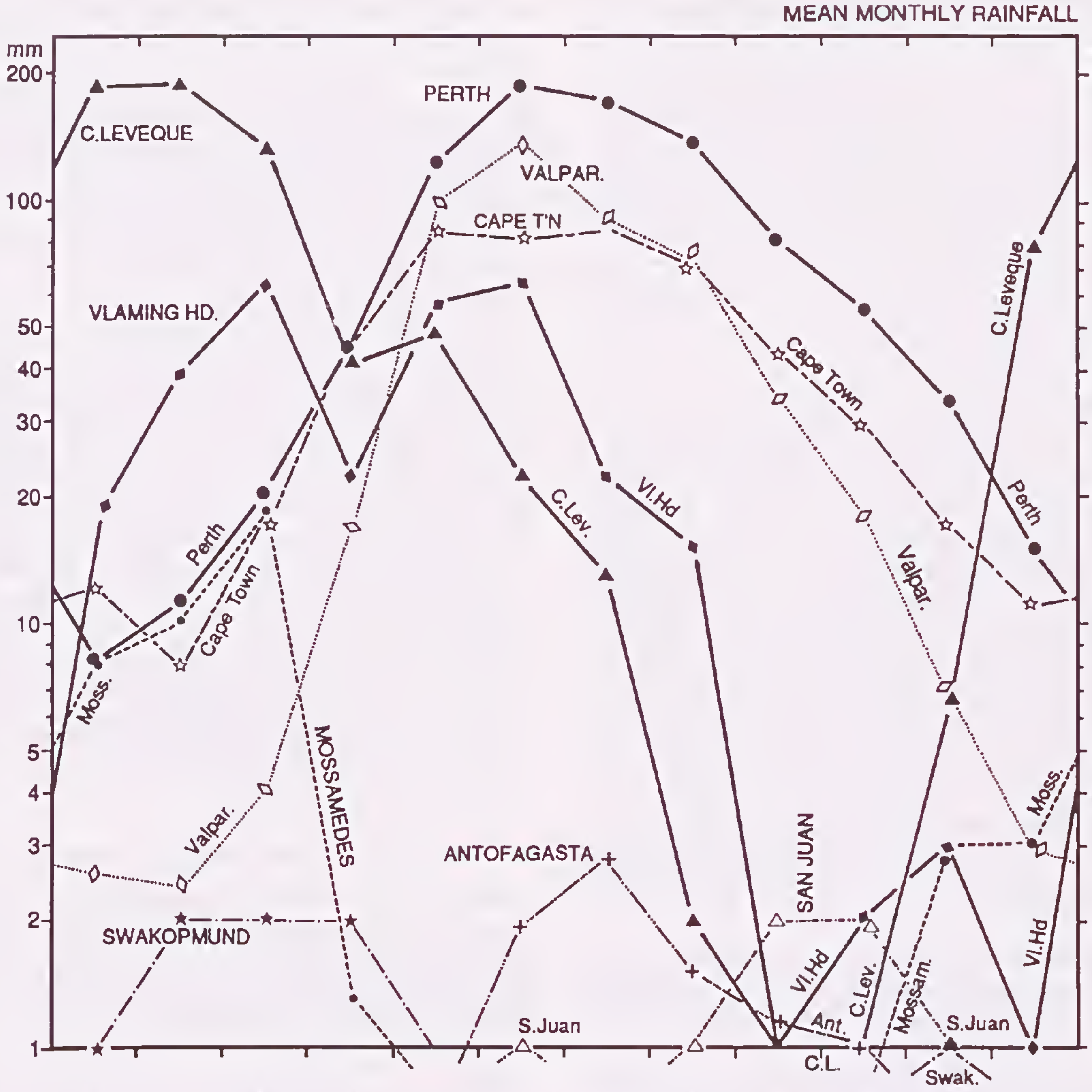

Figure 6 Mean monthly rainfall at Cape Leveque, Vlaming Head and Perth (Western Australia), Mossamedes (Angola), Swakopmund (Namibia) and Cape Town (South Africa), and San Juan (Peru), Antofagasta and Valparaíso (Chile). Note that the scale of monthly rainfall (in mm) is logarithmic, with the base line set at 1.

Dunst in German, *nevel* in Dutch. It is not recorded separately on the land, where it may be counted as fog with better visibility, *eg* in the Australian records analyzed by Maine (1968). It is strongly affected by the time of observations. *Fog*, with visibility under 1 km, is formally called *niebla* in Spanish, *Nebel* in German, *mist* in Dutch. The estimated frequencies of fog from marine observations just offshore are shown in Table 1 as Fog I, those at land stations as Fog II. Fog (or low stratus cloud when it is above the ground) is a major element in the climate of Namibia and Peru and central Chile, contributing a very high relative humidity (daily averages of 75 to 90 % every month) and reducing the amount of sunshine received along a coastal strip some 30 km wide in Namibia, narrower and more broken in Peru and Chile. In Namibia it may penetrate further inland: Brain (1988) during six summer weeks recorded three penetrations of fog some 100 km inland, all within five days. Its main cause is the cooling of the air and the condensation of its moisture content over the colder coastal current or even more so over the upwelling ocean water, or of warmer air advected over surface air cooled by the underlying water. It is suggested here that the initial fog may be denser and more persistent where upwelling ocean waters are cooler than the already cool surface waters, but in hot climates partial evaporation of water droplets results in the much finer garúa.

Table 1.
Yearly number of days with precipitation and allied phenomena.

Lat.	Chile						Namibia, S Africa				Western Australia					
S	Rain	Dr'zle	Mist	FogI	FogII	Haze	Rain	Mist	Fog	Haze	Rain	MistI	MistII	FogI	FogII	Haze
15	5	30	14	7	-	23	6	5	4	38	25	0	3	0	10	9
20	2	1	13	5	0	27	7	6	15	42	23	0	0	1	2	11
25	7	40	13	7	6	25	2	7	19	37	22	8	0	1	0	16
30	15	45	16	9	28	27	15	8	20	30	25	0	1	0	1	10
35	37	n.a.	17	12	54	26	30	9	11	25	50	0	4	3	5	7

Source: Days with rain, mist, fog I and haze calculated as close onshore as possible from McDonald (1938); days with drizzle and fog II for Chile from unpublished official data (Oficina Meteorológica de Chile) averaged from the nearest coastal stations; fog off Africa calculated from Deutsche Seewarte (1944); mist II and fog II in Australia calculated from Maine's (1968) data for Port Hedland and Onslow, Carnarvon, Geraldton and Perth. Fog II for 15°S (Beagle Bay and Broome) and 35°S (Cape Leeuwin) estimated from Loewe (1944). See text for consequences of standardised time of observations at sea.

In western South America there are terminology problems. Blüthgen (1966) quotes Knoch (1930) who describes the garúa as "hovering droplets hardly impeding visibility, with a tendency to accumulate locally, fairly evenly distributed throughout the year". Trewartha (1961) still describes it as a drizzling fog. Conrad (1936) accepts that garúa is clearly distinct from ordinary fog because it behaves differently, "being almost colloidal and - unlike fog - distributed unevenly among unsaturated patches of air". Sekiguchi (1986) defines garúa in northern Peru as 'dry fog': "We are driving a car, the sun is shining, visibility is good and distant scenery is clearly seen - yet the wind-shield gets wet. A film of water covers it. We have to operate the wipers. The black asphalt on the road becomes shiny. If we stop the car and touch it, it is wet... No large fog particles are floating in the air... The relative humidity exceeds 80% every day. In the morning, it is more than 90% almost throughout the year..." The problem is due to the difference in temperature between the land in the daytime and the surface of the sea. The atmosphere over the sea is almost saturated with water vapour. If the saturation vapour pressure of this air is 12-22 mb [hPa] and this air spreads overland, its relative humidity decreases to 50-60%, because the temperature of the coastal area is about 27-28°[C] and its saturation vapour pressure is 37-38 mb [hPa]. Therefore, water evaporates from the fog particles floating in the atmosphere and the particles get smaller. On the other hand a quotation in Knoch (1930) described the garúa at Lima as a fog copious enough to condense in fine droplets, forming a layer some 50 m above the water and 700 to 800 m thick, driven by the southwesterly wind against the seaward slopes. Lima at about 130 m is right in the fog, while its port quarter of Callao remains clear (Fig. 2). By garúa weather the air oozes moisture, umbrellas are quite useless, and the sun may not be seen for months. On the other hand at an altitude of some 800 m one is above the stratus layer and in bright sunshine. Sekiguchi (1986) writes that "the weather of Lima..., because it is enveloped by ordinary fog in the morning the year round, is humid and unpleasant. However, most days the sun shines in the afternoon, the fog turns into garúa and the humidity comes down to 60-70%. It scarcely rains... To avoid this strange and unpleasant climate, people of upper class families send their children to the winter resort Chosica 50 km east of Lima in the foothills of the Andes Range to give them more sun and light. The season of this winter resort is from May through October, when there are many cloudy days... During this season the schools are open."

In southern Peru and northern Chile the dense fog locally known as *camanchaca* (but recorded as *niebla*) is very significant particularly over coastal waters. From about 30°S Chile's long coastal strip is subject to very frequent normal fogs, also recorded as *niebla* (Fog II in Table 1).

Dew, mostly nocturnal and often overlooked by observers, may be the only or the main source of surface moisture in dry regions. From a 1925 paper by Hellmann, Conrad (1936) quotes annual totals of 176 days with dew at Coquimbo and 219 at Los Andes, both in Chile but respectively below and above the inversion layer; the Coquimbo record might be slightly inflated by observations of moisture left behind by early-lifted fogs.

Haze (*calina* or *bruma seca*, popularly also *neblina* in Spanish, *trockener Dunst*, often plainly *Dunst* but at times also *Nebel* in German, *nevel* in Dutch), mostly caused by dust or salt particles, is not a form of precipitation. It is normally carried over these regions by dry offshore winds. The table shows that it is frequent off Chile, and even more frequent off Namibia, which both have very arid coasts and practically no plant cover at these latitudes. Its frequency off Western Australia, where aridity is less extreme, is much lower and shows a definite maximum near the tropic.

Seasonality of precipitation

At the northern end of the three regions (15°S) rain at sea is more frequent in summer, but the frequency ranges from 12% of the observations in Western Australia (with notable contributions from monsoons and tropical cyclones, Fig. 4) to 6.5 in Namibia and only 1% in Chile, where the Andes are a forbidding barrier (Figs. 2 and 6).

About 20°S summer rains are still noticeable in Namibia and Western Australia, whereas they are negligible in Chile. From this latitude southwards winter rains become more frequent in Namibia, and even more so in Western Australia, where they become dominant and reach 15% of the observations.

At latitudes 25 to 30°S regional differentiation becomes even more pronounced, with moderately frequent rains being concentrated in the winter in Chile, spread to winter and spring in Namibia, and most abundant from late autumn to early spring in Western Australia.

The transition to mid-latitude climates with more uniform rains may be seen at the southern end of each of the three regions where the percentage of rainy days in each season, beginning with summer and with the winter percentage in italics, is about 4+7+*22*+8% of the observations in the four seasons off Chile, 5+8+*11*+7% off South Africa, and 5+10+*21*+15% off Western Australia. These values may be compared with the monthly averages for coastal land stations in Fig. 4.

Mist is not frequent, and may be observed in any season off Chile, more in spring off Namibia, and, though uncommon, mostly in winter off the Exmouth Peninsula (mist I in Table 1) and on the Western Australian coast (mist II, usually merged with fog data).

Although the theory of its formation is very well known, fog is so closely affected by the conditions of the underlying surface (and some subjective judgment by the observer, for example Köppen 1931, Conrad 1936) that observations present many practical difficulties, including the timing of the observations themselves because fog is so readily dissipated by thermal and dynamic factors, being very frequently a nocturnal and early-morning phenomenon which on land would most often escape the Australian 9 am observing time, and certainly in summer even the South African 7 or 8 am observations. At a land station, even a short period of fog any time in the 24 hours should result in a "day with fog" being recorded. Noon at Greenwich (the time of observations at sea) corresponds to about 7:30 h off Chile, 13:00 off Namibia, and 20:00 off Western Australia, leading to a fairly adequate assessment of "days with fog" off Peru and Chile (where Blüthgen (1966) shows over 40 days per year between about 18°S and the tropic, fewer further south), a greatly reduced assessment except in winter off Western Australia, and an almost total exclusion off Namibia, where on the other hand Blüthgen (1966) charts over 80 days with fog per year.

The glaring differences between sea and land (Fog I and Fog II) observations in Table 1 show just one example, or perhaps one result, of these difficulties. Fog occurs moderately throughout the year, but more often in autumn and winter, off Chile. It forms more readily onshore and is a semi-permanent feature at altitudes of a few hundred metres on the slopes of the Andes (Fig. 2). It is more frequent in autumn and spring off Namibia (Deutsche Seewarte 1944), but after a specialist workshop at the end of 1988 Shannon *et al.* (1989) could still write that "even the formation of fog was shrouded by ignorance and clouded by speculation." The same workshop stated that "research on fog formation, movement and chemistry in the Namib-Benguela is necessary in view of the important role which fog plays in the system. Even at a very basic level, the contribution that upwelling makes in fog generation and in the maintenance of the aridity of the Namib needs to be established."

In Western Australia fog is uncommon, and at sea almost exclusively an autumn phenomenon (summer and early autumn according to the very detailed maps by the Koninklijk Nederlands Meteorologisch Instituut 1949). Onshore the very infrequent fogs occur mostly in winter and early spring (Maine 1968); there is a secondary peak in February at Carnarvon, March at Onslow, Geraldton and Perth, and April at Port Hedland. At Geraldton winter has few days with fog, and the main peak is in September-October.

Haze, generated by dry conditions and therefore affected by the timing of observations in almost the opposite way to dew, is recorded more frequently in the summer off Chile and Western Australia and practically throughout the year off Namibia, with a maximum in the autumn. Shannon *et al.* (1989) advocate research into its contribution of minerals to offshore waters. Off Chile the distribution, apart from the summer, is relatively even throughout the year, whereas in Western Australia the frequency and abundance of rains prevent the mobilization of dust once the summer drought is over. However, Keough (1951) gives an annual average of about 3 dust storms for Geraldton (adding that "dusty conditions are more frequent in late summer with NE to SE winds") and about 5 for Port Hedland. At Carnarvon "dust storms occur occasionally and dust often accompanies the onset of SSW breeze". At Kalgoorlie "dust storms occur on 13 days per year." The recording of the far more frequent dust haze is obviously inadequate, as is that of smoke haze in the South West.

Upper air correlations

A pilot study of some upper air comparisons, based on NOAA's Climatic Data for the World, was shown in Fig. 3. A very significant factor in the formation of rain is the dew point, of which upper-air cross-sections are given in Fig. 7. It should be noted that Australian observations do not extend above 500 hPa.

Regional differences stand out very clearly. Above Perth there is a gradual transition from 2°C at the surface in June and early July to 15° or 20°C at 700 hPa (about 3000 m). Above Cape Town a surface average of

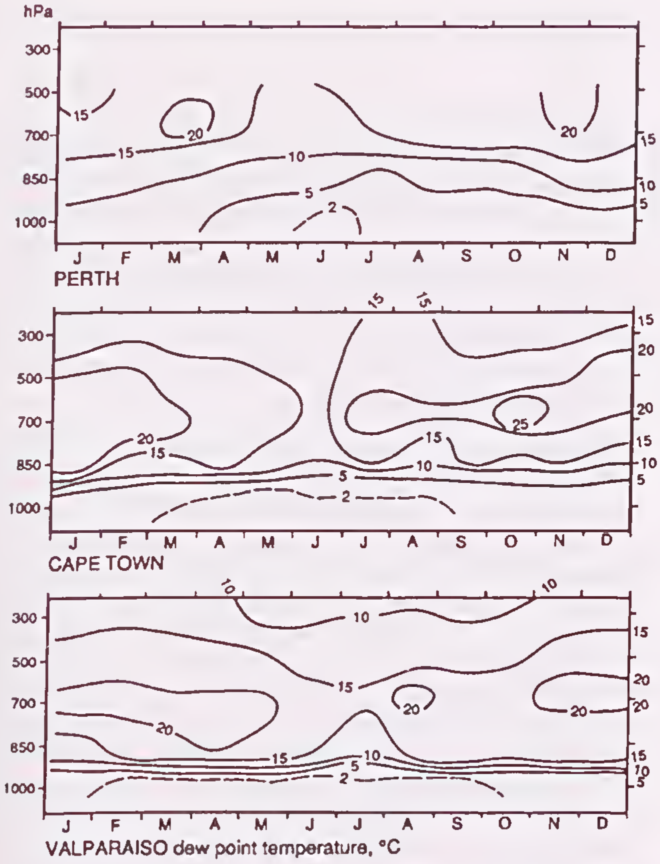

Figure 7 Dew point temperatures above Perth, Cape Town and Valparaíso. Notice the differences: very smooth change with altitude above Perth, rapid change from 5° to 10° and at times 15°C above Cape Town, and rapid change from 2° to 15°C (from below to above the inversion) above Valparaíso.

less than 2°C lasts from March to early September, but in altitude temperatures above 20° are far more prevalent, both vertically and seasonally, than above Perth. Above Valparaíso a marked atmospheric stratification is evident, with isotherms running parallel or nearly so at most heights: the surface dew point is below 2°C from February to mid-October, while dew points above 20° are mostly confined to the 700 hPa band.

The most significant difference between the three stations is in the stratification below 1000 m (well below 850 hPa): as the figure shows, this stratification is non-existent above Perth, continuous but with a range of some 5°C above Cape Town, and even more solid, with a range of some 10° to 13°C, above Valparaíso. This is evidence of almost permanent atmospheric inversions, particularly above Valparaíso, which prevent convective activity - thunderstorms and hail have hardly ever occurred at some Chilean stations.

Upper air and rainfall relationships

A preliminary survey was undertaken of correlations between conditions and movements of the upper air and monthly average rainfall at the underlying stations. A small part of the results is given in Fig. 8, which shows correlations (R^2) between each station's actual monthly rainfall and the upper air conditions or movements for the same month, for the month before, and for two months before. To the left are the correlations with upper air temperature, to the right those with geostrophic wind speed at the various levels.

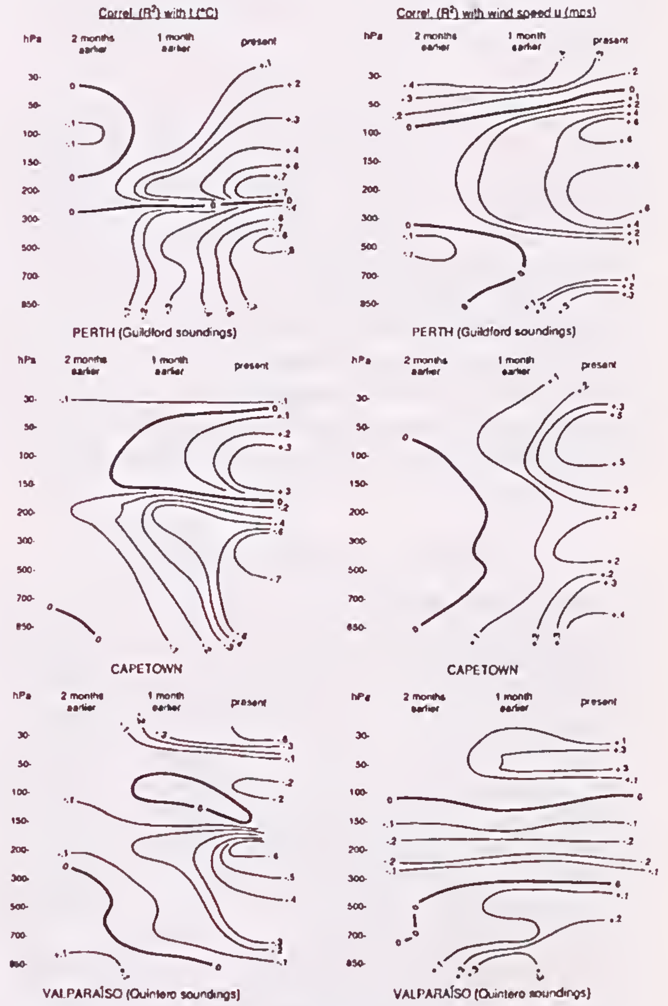

Figure 8 Correlation (R^2) between average monthly rainfall and upper air temperatures (diagrams to the left) and wind speed (diagrams to the right) above Perth, Cape Town and Valparaíso.

At substratospheric heights (200 hPa) above Perth warmer air is closely and positively associated ($R^2 \geq 0.7$) with the rainfall of the same month; this association may be forecast to some extent ($R^2 \geq 0.3$) on the basis of the previous month's 200 hPa temperature. A similar association is much weaker above Cape Town, and non-existent above Valparaíso.

The three regions show a similar but negative relationship (the colder the air above, the greater the rainfall below) at lower levels, but the actual levels of greatest significance differ for each station. Above Perth the closest association ($R^2 \geq 0.8$) is found at 500 hPa; it persists downwards, only slightly reduced, and was also noticeable a month earlier. Above Cape Town a negative correlation between temperature and underlying rainfall ($R^2 \geq 0.7$) is found from 500 to 300 hPa, a higher and thicker band; it also extends downwards with only a slight loss of closeness ($R^2 \geq 0.6$), and is also noticeable the previous month. Above Valparaíso the correlation is still negative, but conditions are quite different: $R^2 \geq 0.6$ is found at 200 hPa but the closeness of the correlation decreases steadily downwards, to become negligible as it reaches the impenetrable inversion below 850 hPa.

Other, related differences are noticeable in the relationship between upper air winds and rainfall at the surface. Above Perth between 100 and 300 hPa (16 500 and 9500 m) runs an enormous band of strong westerlies (Fig. 3) which are closely and positively associated with the rainfall below ($R^2 \geq 0.6$). Above Cape Town the association is slightly weaker and limited to 50 to 100 hPa. Above Valparaíso the correlation, possibly just significant ($R^2 \geq 0.3$), is restricted to 50 hPa (20 500 m) but begins already in the preceding month; the mechanism of any relationship is worth further investigation. However, no relationship between wind speed and surface rainfall seems to exist at any level below 50 hPa.

Regional thermal differences

World maps of January and July temperatures, from the masterly pioneer maps by van Bebber & Köppen in Hann (1896) to Blüthgen (1966), clearly show regional differences, particularly above offshore waters. In January wedges of air below 20°C reach northward beyond the tropic along the coast of Chile (and along the foot of the Andes) and just off Namibia above the upwelling of cold water from Port Nolloth to Walvis Bay (Höflich 1984). In Chile a core wedge of air below 15°C normally occurs as far as 32°S; there is no counterpart off Namibia. No cool air wedge is shown off Western Australia, on the contrary, surface offshore air above 30° reaches about 20°S (mention of tropical cyclones above). In Angola inland air above 30° just reaches the coast around 18°S; coastal and offshore air off Peru and north Chile stays below 25°C.

Differences are simpler and sharper in July: offshore air below 20°C reaches northward to about 18°S in Western Australia, 8°S off Angola and about 3°S off South America.

In general, maximum and minimum screen temperatures are 6° or 7°C higher at Cape Leveque (16°24'S, Western Australia) than at Mossamedes (15°12'S, Angola) and 7° to 9° higher than at San Juan (15°22'S, Peru), as may be expected from the differences in the adjoining ocean surface temperatures. At Exmouth (24°49'S, Western Australia) mean maximum summer temperatures rise over 16°C above those at Swakopmund (22°41'S, Namibia) and 12° above those at Antofagasta (23°26'S, Chile), but by winter both are reduced to some 4°C. Summer minima are about 6° higher at Exmouth than at Antofagasta, where in turn they are some 2° higher than at Swakopmund. Similar differences are found in winter minima.

Further south, Perth summer maxima are only some 3° above those at Cape Town, but about 8° above those at Valparaíso; summer minima are 2° higher than Cape Town's and over 5° higher than Valparaíso's. In winter travelling anticyclones bring frequent, if transient, inversions over Perth, reducing the differences from the permanent inversions of southwest Africa and Chile. Winter maxima at Perth and Cape Town are very similar, and those at Valparaíso only 2° lower. Winter minima are similar at Perth and Cape Town, and about 1° lower at Valparaíso.

In these regions water masses (and very maritime air) can hold the mean daily range at 5 to 7°C, land masses (and very continental air) can send it soaring to 15 or 18°C. Air circulation therefore determines the season or the month when the greatest or smallest range occurs. Thus at Cape Leveque the narrowest range occurs during the strongest onshore air flow in January-February and the widest one during the anticyclonic offshore flow in July-August, whereas at Vlaming Head the narrowest one comes in June (northwesterly epitropical disturbances and extreme reach of southwesterly mid-latitude fronts) and the widest one in September and also in November-December (probably due to phases in the transit of anticyclones). Loewe (1948) showed that in Australia wider diurnal ranges of temperature as well as higher interdiurnal variability of temperature occur during the drier seasons, *ie* in winter north of the tropic and in summer south of it. On the other hand in western Namibia and South Africa the greater variability occurs in winter and early spring, when the hot dry berg winds descend from the plateau often enough to raise daily maximum temperatures. "In the Namib Desert... the mean monthly temperatures vary little but daily temperatures vary widely and relatively unpredictably..." (Seely 1989).

The influences of cool ocean currents, continental geometry and landforms combine in producing another clear regional differentiation: in tropical Western Australia the month with the greatest mean daily range of temperature, 10 to 15°C, progresses gradually from July at Cape Leveque to October beyond Onslow. In the other regions there is no regular time sequence and the range remains smaller: 10°C in May at Mossamedes, 9.5° in April at Lima and 7.8° in January to March at Arica.

Oceanic influences and onshore air flow combine in giving the southern reaches of all three regions mean daily ranges of 5 or 6°C in June-July, but only along the South American coast where the flow of cool water along the shore is at its strongest does this pattern continue very far towards the equator. On the southwest African coast, where local cool water upwelling is very effective and the cool current is weaker, the months with the narrowest range vary with each station; in Western Australia the time remains unchanged as far as Shark Bay but daily ranges below

6°C are only found on islands, thus confirming the fact that plain oceanic influence is the prime factor in holding thermal ranges small.

The delayed annual thermal maximum in March (in April for mean daily maxima) which occurs around Broome in Western Australia, is also found at Mossamedes in Angola, and is probably due to the time of the second transit of the zenithal sun, the position of travelling anticyclones, and the end of the rainy season. On the Peruvian and Chilean coast the warmest time is more diffuse, probably because of the strong ocean current along the shore, but a faint maximum is usually found in February, as is normal and more definite further south in all three regions.

Conclusions

Evidence so far does not clearly prove any effect of the Leeuwin Current on coastal climates, partly because of deficiencies in the available records of the pairs Abrolhos-Geraldton and Rottnest-Fremantle. At the ocean-air interface, higher temperatures and levels of humidity may be noticed physiologically. As a stream, the Leeuwin Current is only about 30 km wide (Godfrey & Ridgway 1985), although some of its eddies may reach much further to the seaward. Mean minimum temperatures are higher at Rottnest Island than at Fremantle by 1°C in March, 1.4° in April, 1.8° in May: the April-May rise may be partly due to the arrival of warmer water. This suggestion may be supported by the fact that 9 am relative humidity, relatively stable, shows its greatest monthly increase from March to April: 8% at Rottnest, 16% at Fremantle and 9% at Perth, but on the other hand these changes are even more conspicuous further inland, where no significant influence of the Leeuwin Current could be postulated. Karelsky (1961), having defined 'cyclonicity' as the number of cyclonic centres in a particular area during the month concerned, shows an average cyclonicity of 0.6 in March, 1.3 in April, 1.5 in May and 1.9 in June between 30 and 35°S and 110 and 115°E. On the other hand, most rain is brought to south-western Australia by mid-latitude fronts linked with mid-latitude depressions which form over the southern Indian Ocean south of 45°S and west of 75° or 80°E. A count for 1988-1990 shows rain brought to Perth by nearly 100 weather systems a year, some 84 of them meridional fronts formed far to the south-west and crossing over Perth or further south, but including also a dozen 'subtropical' lows formed hundreds of kilometres due west of Perth. The monthly count of rain-bearing fronts agrees with the average of 9.5 fronts (including non-rain-bearing ones) in February and 14 in August shown by Gorshkov *et al.* (1974). Some rain was brought by coastal troughs and by two tropical cyclones. Cloud formations were already conspicuous in satellite images days before they reached the vicinity of the Leeuwin Current. It is possible that some 'subtropical' lows (more frequent in the autumn) and some troughs, slow-travelling or even briefly stationary, could gather additional vapour from the Leeuwin Current, but their formation and main moisture loading took place hundreds of kilometres away.

The most significant and economically important inter-regional climatic differences, particularly in the amount of rain received, are due to the absence of colder water near the Western Australian shore, not to the presence of warmer water: Gorshkov *et al.* (1974) show an average of 14 fronts reaching the coast near Perth in August, against 4 reaching Chile at the same latitude. As to nor'westerly origin of epitropical storms or cloud bands, the water vapour generated by 2.5 million km^2 of warmer water in the Arafura-Cocos region far outweighs what can be generated by the 25 000 km^2 or so of the Leeuwin Current, even when its surface is greatly increased by meanders, swirls and gyres. Air transiting across the current may be made more unstable, but most of the winter thunderstorms seem to be due to the sudden uplift of the fast windstream by the Darling Scarp (Gentilli 1979b).

Immediately above the 'climatic cuticle' affected by the Leeuwin Current is likely to be spreading the mild cooling effect of the much broader West Australian Current, carried by the peripheral winds of the Indian Ocean anticyclone, and partly showing cyclonic divergence long before it meets the western margin of the Leeuwin Current.

In principle, it seems desirable to establish regular climatic observations at the Abrolhos and to extend the scope of the Rottnest ones, particularly in the afternoons. It should also be recommended that detailed studies of sea breezes, land breezes and southerly coastal wind be supported as long-term research projects.

Evidence of contemporary climatic fluctuations should be monitored regularly. Gentilli (1952b, 1971) showed definite patterns (decrease in the Kimberleys, increase in the South-West) for the period 1881-1940. Pittock (1975) found a reversal of this trend after 1941. Vogel's (1988) research seems to show that in 160 years of Cape Town records there is no indication of climatic change, but his graphs reveal definite and fairly regular fluctuations of floods and droughts. Perhaps there is a need for some well-publicised agreement on definitions of climatic singularities, variations, periodicities and fluctuations, and long-term climatic changes, while trying to avoid the stereotyped rigidity that made the concept of 'climatic normal' almost meaningless to research.

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